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DESIGN OF H^2 STEERING CONTROLLER IN CORPORATION WITH SPEED CONTROL

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Abstract. *The path following control is the common control strategy for making a vehicle follow desired paths. However, when only the lateral motion of the vehicle is controlled, non-negligible deviations in the vehicle position are often caused. Aiming at suppressing those deviations, this research addresses a combined design of the speed and steering controls. We newly propose to adjust the vehicle's speed according to the current tracking errors. Subsequently, we derive the linearized motion equations under that speed control and design the steering control based on the standard linear H^2 control theory. As for verifying the effectiveness, comparative simulations are conducted according to whether the proposed speed control is applied or not.*
Keywords: Speed control, Steering control, H^2 control, Path following method, Control design, S-shaped curve

1. **Introduction.** In recent years, the automobile industry has seen soaring fuel costs and reducing carbon dioxide missions. It has been taken up as a problem. In response to these problems in Japan by 2035 policy has been made to make all vehicles sold in Japan electric vehicles. However, the price of electric car bodies in Japan today is expensive. Even if the tank is fully charged, it has problems such as the mileage being inferior to that of a gasoline car. Therefore, regardless of whether it is a gasoline or an electric vehicle, we will consider autonomous driving to improve the problem of fuel cost and exhaust gas of automobiles. The merits of autonomous driving are the prevention of accidents due to human error and the driver's securing free time can be mentioned, but it is also thought that there is an improvement in fuel efficiency.

From the theoretical point of view of human-machine systems, human handling operations are generally treated as linear continuous-time feedback control, expressed as transfer functions, and transfer function models suitable for driving conditions have been proposed [1]. The utilization of autonomous driving reduces idling when waiting for traffic lights and traffic jams. Fuel consumption can be diminished, and the location information is linked with surrounding cars to grasp the road condition. If possible choose the route it wants to drive by avoiding traffic jams, this drive while reducing unnecessary fuel consumption and stress. Furthermore, if we focus not only on fuel efficiency but also on safety, reckless driving that closes the distance between vehicle in front results collision. However, problems such as rear-end collisions with pedestrians due to human error may occur. If AI operates the car in autonomous driving, these can be prevented in advance. On the other hand, there is a liability problem in the event of an accident and the use of

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network technology. Disadvantages include being vulnerable to hacking because it communicates between cars. Therefore, it is carefully designed so as not to cause an accident, and high-performance autonomous driving is required.

High-performance autonomous driving requires the vehicle's trajectory to follow. To achieve this, if steering control can be performed, the car can follow the target track. However, in the previous research [3], only foreseeing control was performed as steering control on the dynamic model of the vehicle without speed control, and the tracking performance of the S-shaped track was investigated when the case was divided into cases by the predicted time and the speed of the vehicle. As a result of this study, even if there is a reaction delay, if there is a foreseeable time, the actual vehicle follows the reference track well. However, if the prediction time is 0[s], the actual vehicle is lagging when it turns a large curve in the track. After that, the actual vehicle caught up and the final destination point of the virtual vehicle and the actual vehicle was shifted, resulting in a deviation in the direction of the car body. Therefore, speed control is performed to eliminate deviations. Steering and speed control are often performed separately [1], but in this study, steering and speed control are performed. Even if the prediction time of the problem of the preliminary research is 0[s], the deviation in the direction of the car body is suppressed, so as a newly proposed speed control, a linear control that can suppress the deviation in the direction of the car body is applied. On the other hand, the H^2 control is applied to the steering control. H^2 control is a control method that controls the size of the H^2 norm, and the smaller the H^2 norm of the signal, the faster the response. Therefore, it is excellent as a measure of good transient response [4]. Humans efficiently maneuver vehicles by predicting the course ahead of the vehicle and predicting the vehicle's course of travel. It incorporates human functions and uses futuristic information to improve control performance called predictive control [3]. In addition, there is a method using predictive control for autonomous driving, and H^2 control also leads to solving the problem of predictive control. Both steering and speed control is applied to the motorcycle model, and the deviation between the virtual vehicle and the actual vehicle when the speed V_{ref} of the virtual vehicle or the weight ρ concerning the steering in the generalization plant of the H^2 controller is changed to follow the reference trajectory of the S-shaped curve is verified by simulation. However, the speed of the virtual vehicle was assumed to be at a constant speed [6].

This paper is organized as follows. In Section 2, the problem formulation of the vehicle system is presented. In Section 3, the design procedure of the speed control and steering control is explained. In Section 4, the features of the resulting controller are illustrated by the numerical simulations. In Section 5, the conclusion is explained.

2. Problem Formulation.

In this section, we model a vehicle system and formulate a problem for path-following control. According to [2], an error system is derived that describes the error between the actual vehicle and the virtual vehicle running on the path. The differential equation describes the trajectory of the actual vehicle.

$$\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\phi}(t) \end{bmatrix} = \begin{bmatrix} V(t)\cos(\phi) \\ V(t)\sin(\phi) \\ r(t) \end{bmatrix} \tag{1}$$

where $V(t)$, and $r(t)$ are the linear velocity and yaw rate, respectively, while the virtual vehicle on the reference trajectory follows the differential equation.

$$\begin{bmatrix} \dot{x}_{ref}(t) \\ \dot{y}_{ref}(t) \\ \dot{\phi}_{ref}(t) \end{bmatrix} = \begin{bmatrix} V_{ref}\cos\phi_{ref}(t) \\ V_{ref}\sin\phi_{ref}(t) \\ r_{ref}(t) \end{bmatrix} \tag{2}$$

We note that, by the geometric condition, V_{ref} and $r_{ref}(t)$ should be related by the equation.

$$r_{ref}(t) = V_{ref}\kappa_{ref}(t)$$

where $\kappa_{ref}(t)$ is the curvature of the reference path.

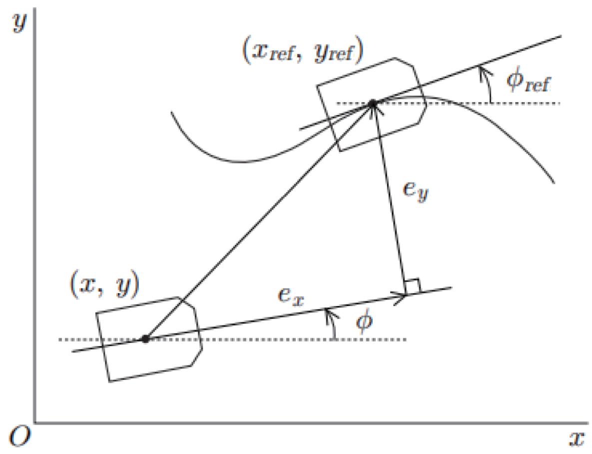


FIGURE 1. Relation between actual and reference vehicles

As shown in Figure 1, the path-following method focuses on the cross-track error

$$\begin{bmatrix} e_x(t) \\ e_y(t) \\ e_\phi(t) \end{bmatrix} = \begin{bmatrix} R^T(\phi(t)) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_{ref}(t) - x(t) \\ y_{ref}(t) - y(t) \\ \phi_{ref} - \phi(t) \end{bmatrix}, \quad R(\phi(t)) = \begin{bmatrix} \cos\phi(t) & -\sin\phi(t) \\ \sin\phi(t) & \cos\phi(t) \end{bmatrix} \tag{3}$$

By direct calculation, we have the error system

$$\begin{bmatrix} \dot{e}_x(t) \\ \dot{e}_y(t) \\ \dot{e}_\phi(t) \end{bmatrix} = \begin{bmatrix} \omega(t)e_y(t) + V_{ref}\cos e_\phi(t) - V\cos(t) \\ -\omega(t)e_x(t) + V_{ref}\sin e_\phi(t) - V\sin(t) \\ \omega_{ref}(t) - \omega(t) \end{bmatrix} \tag{4}$$

As a weakness of the steering control in the previous research [3], it has been found that when the curvature of the reference trajectory is large, the trajectory following error in the longitudinal direction of the vehicle body cannot be suppressed even if the prediction time is extended. Therefore, in this research, we will clarify the linkage method between the speed control method and the steering control method to suppress the longitudinal tracking error of the vehicle body. The purpose of this paper is to reduce the error between the actual vehicle and the virtual vehicle traveling on the path.

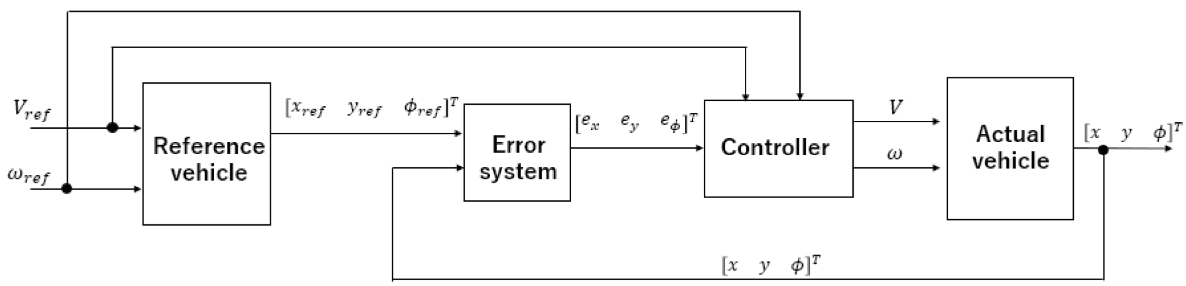


FIGURE 2. The control block diagram

3. **Control Design.** This section presents the control design necessary for formulating the path following the control problem in the vehicle system setting. As shown in Figure 3, the relation of speed control ends steering control and structure overall controller. In Subsection 3.1 define an expression to adjust the speed. Subsection 3.2 shows the generalization plant when applying the error system and kinematics model for $e_y(t)$, $e_\phi(t)$.

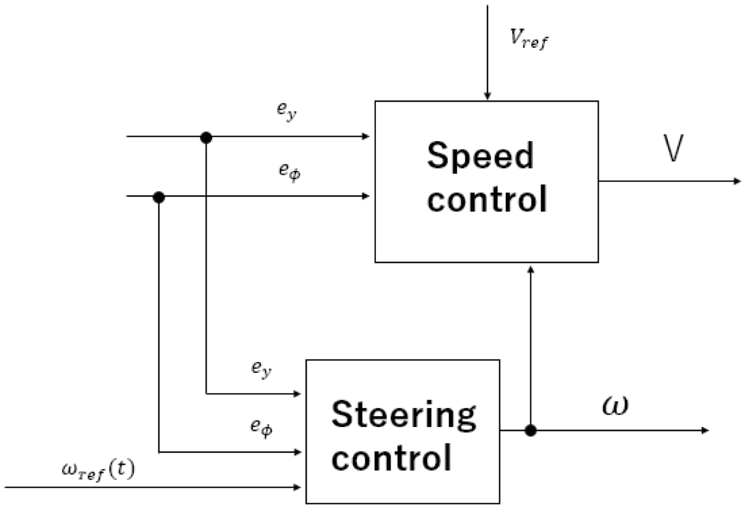


FIGURE 3. Structure overall controller

3.1. **Speed control.** Focusing on the x component of (4), assuming that $\dot{e}_x(t) = 0$, the velocity V is

$$V(t) = \omega(t)e_y(t) + V_{ref}\cos e_\phi(t) \tag{5}$$

If it holds that $\dot{e}_x(t) = 0$, $e_x(0) = 0$

$$e_x(t) = 0 \tag{6}$$

In addition, the speed is

$$V = \omega(t)e_y(t) + V_{ref}\cos e_\phi(t) \tag{7}$$

3.2. **Steering control.** This section shows the generalization plant when applying the error system and kinematics model for e_y, e_ϕ. The error system for e_y, e_ϕ found in Subsection 3.1 follows the following equation

$$\begin{bmatrix} \dot{e}_y(t) \\ \dot{e}_\phi(t) \end{bmatrix} = \begin{bmatrix} 0 & V_{ref} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e_y(t) \\ e_\phi(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \omega_{ref}(t) + \begin{bmatrix} 0 \\ -1 \end{bmatrix} \omega(t) \tag{8}$$

Generalized plants can set up problems for follow-up control and robust control and organize solutions. In this section, generalized plants are represented according to the kinematics model. The generalized plant is set up as shown in Figure 2, and the control target and the controller are represented by G and K, respectively. $w = \omega_{ref}$ is the exogenous input, $u = \omega$ is the control input,

$$z = \begin{bmatrix} e_y(t) \\ e_\phi(t) \\ \rho\omega(t) \end{bmatrix} \tag{9}$$

is the controlled quantity, and

$$y = \begin{bmatrix} e_y(t) \\ e_\phi(t) \end{bmatrix} \tag{10}$$

is the observed quantity.

Suppose that the generalized plant $G : (w, u) \to (z, y)$ is given by the following state-space realization:

$$G(s) = \left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & 0 & D_{12} \\ C_2 & D_{21} & 0 \end{array}\right] \tag{11}$$

When we apply a kinematics model to generalized plant G, its state-space realization is given by

$$G(s) = \left[\begin{array}{cc|cc} 0 & V_{ref} & 0 & 0 \\ 0 & 0 & 1 & -1 \\ \hline 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \rho \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{array}\right] \tag{12}$$

4. **Simulation Results.** The simulation shows the results with or without speed control and with the generalized plant weights ρ for steering to 1 and 0.01, respectively. The simulation time was 100[s], and the curvature of the reference orbit expresses an S-shaped curve with a radius of 460[m]. The simulation was performed by dividing the weight ρ for steering in the generalization plant into (a) and (b) cases.

(a1) When the speed of the virtual vehicle speed $V_{ref} = 30$[m/s], $\rho = 1$ with speed control

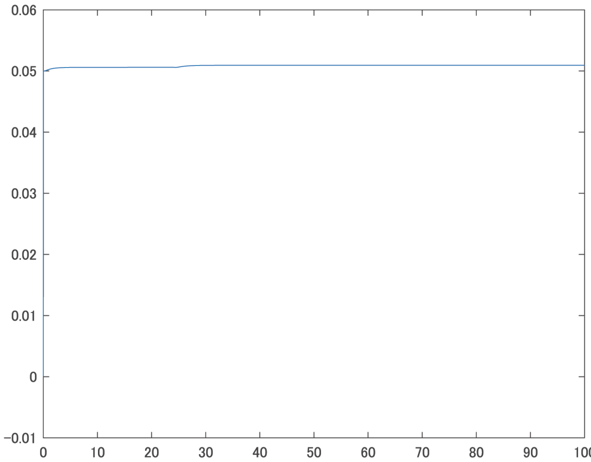
(a2) When the speed of the virtual vehicle speed $V_{ref} = 30$[m/s], $\rho = 1$ without speed control

(b1) When the speed of the virtual vehicle speed $V_{ref} = 30$[m/s], $\rho = 0.01$ with speed control

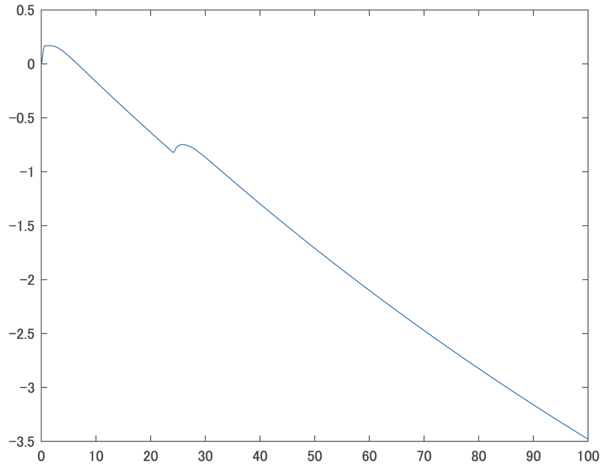
(b2) When the speed of the virtual vehicle speed $V_{ref} = 30$[m/s], $\rho = 0.01$ without speed control

When comparing the case where the speed control was performed above and the case where the control was not performed as $V(t)= V_{ref}$, a large difference was found in $e_x(t)$. As time passed without speed control, the deviation e_x increased. On the other hand, when speed control was performed, it converged around 0.05[m] even after time had passed. (a) When comparing the simulation results of (b), $e_x(t)$ and $e_y(t)$ showed no difference in the waveform, but when we focused on $e_\phi(t)$, (b) converged more quickly to the stationary value. From this, the smaller ρ, the better the responsiveness. However, if ρ is set too low even if the response is improved, the direction will change rapidly, which may cause safety problems, so it is necessary to pay attention to the physical burden on the driver for the ρ number.

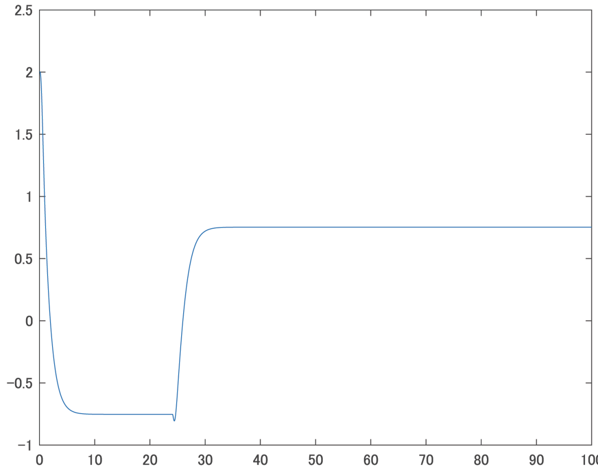
5. **Conclusion.** To improve the problem presented in a previous study in [5], where a simulation was performed under the condition of 0[s] lookahead time, it was assumed that the predictive control could not be applied to the simulation. The deviation in the direction of the vehicle body occurs when the simulation is performed under the condition that the lookahead time is 0[s]. Considering the cause, in the simulation of this previous study, steering control was applied to the vehicle, and speed control was not applied. This caused a delay between the virtual vehicle and the actual vehicle turning heavily when turning a curve, resulting in a deviation in the endpoint. Therefore, we thought of a control that applied both steering control and speed control so that it could catch up even when the actual vehicle lagged.



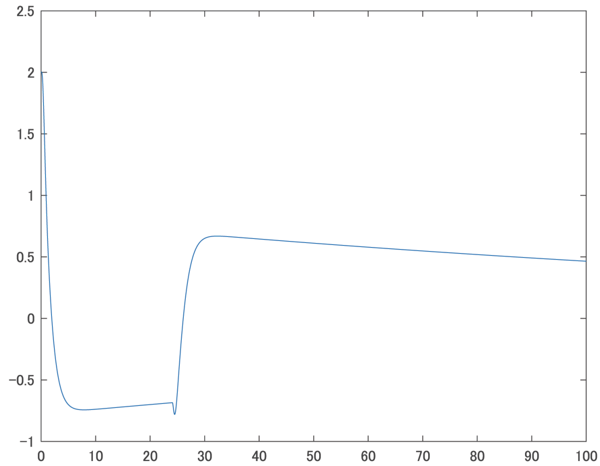
(a1) e_x with $V_{ref} = 30$, $\rho = 1$



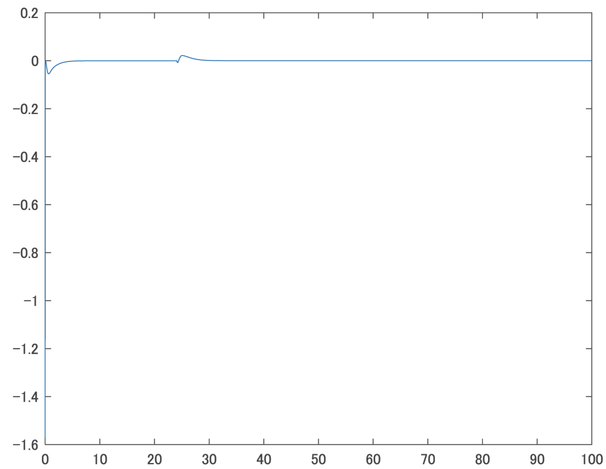
(a2) e_x with $V = V_{ref}$, $\rho = 1$



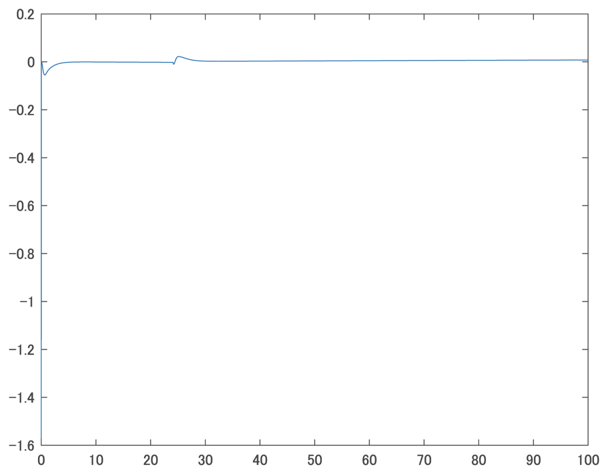
(a1) e_y with $V_{ref} = 30$, $\rho = 1$



(a2) e_y with $V = V_{ref}$, $\rho = 1$

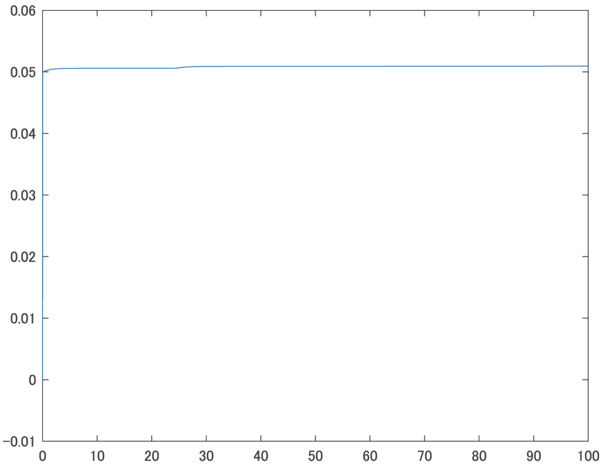


(a1) e_ϕ with $V_{ref} = 30$, $\rho = 1$

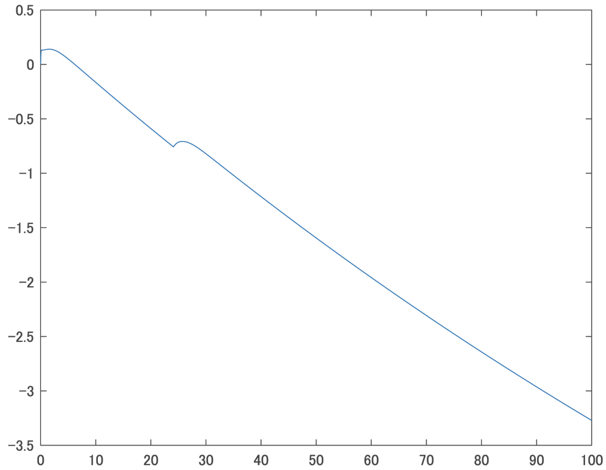


(a2) e_ϕ with $V = V_{ref}$, $\rho = 1$

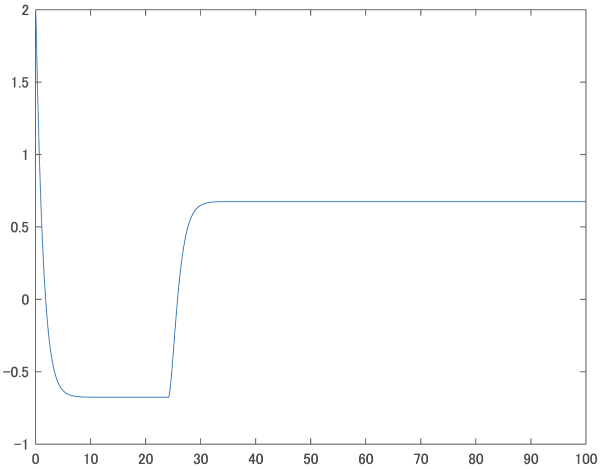
(continued)



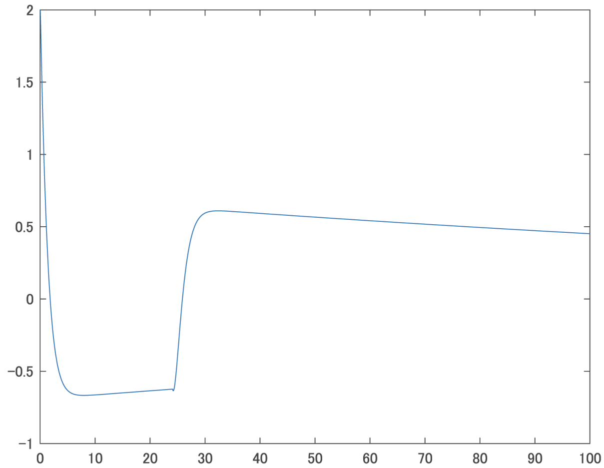
(b1) e_x with $V_{ref} = 30$, $\rho = 0.01$



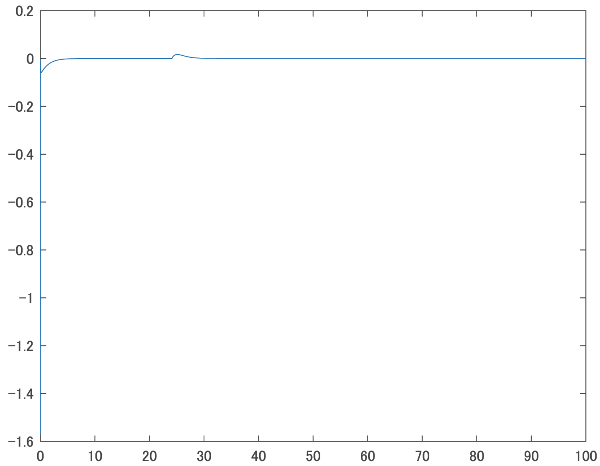
(b2) e_x with $V = V_{ref}$, $\rho = 0.01$



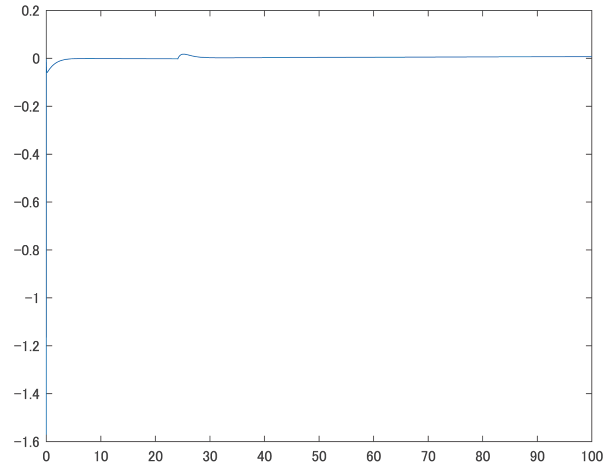
(b1) e_y with $V_{ref} = 30$, $\rho = 0.01$



(b2) e_y with $V = V_{ref}$, $\rho = 0.01$



(b1) e_ϕ with $V_{ref} = 30$, $\rho = 0.01$



(b2) e_ϕ with $V = V_{ref}$, $\rho = 0.01$

Figure 4. Simulation result

As a result, the deviation $e_x(t)$ in the direction of travel of the car body became larger as time passed when $V(t) = V_{ref}$. On the other hand, when the speed was controlled and the simulation was performed, it was sufficiently suppressed, and the purpose of this study was to suppress the deviation in the direction of the car body, and when ρ was changed, the smaller the size, the better the responsiveness.

We considered improving the tracking performance by applying the servo system described in [2]. However, this servo system is unsuitable for this research's kinematics model. However, the kinematics model used in this study cannot improve the tracking performance of this servo system, so a simulation using a dynamics model is a future issue. Therefore, simulation using a dynamics model will be a future issue. Furthermore, experiments using an actual machine will be necessary if the control performance can be improved. The experiment using the actual machine will be necessary if the control performance can be improved.

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